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Influence of Altitude and Aspect on Daily Variations in Factors of Forest-Fire Danger

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CONTENTS

INTRODUCTION

Altitude, in broad subdivisions, exerts recognized and well-understood effects on climate. Aspect further modifies the altitudinal influence. Many publications have dealt with the interrelations of these geographic factors with climate and life zones or have discussed variations of individual weather elements as influenced by local altitude and aspect differences and the resultant effects on vegetation types, frost belts, thermal belts, phenology of plants, water resources, and agricultural economics in mountainous countries. Such variations have never before been systematically investigated, however, to determine their relation to forest-fire control, which in

[1] "Forest-fire danger" as used in this article is a general term expressing the total of all factors which determine whether fires will start, spread, and do damage. This study is concerned only with the variable factors of fire danger which contribute to rate of spread, namely, wind velocity and fuel moisture and their controls. The term "fire behavior" will be used to express their integrated value.

[2] The author has been in charge of the research project reported in this circular since the spring of 1935. The project was planned and put into operation in 1934 by H. T. Gisborne, who with the aid of G. M. Jemison and J. M. Armstrong, located and prepared sites for the altitude and aspect stations, installed equipment, and collected preliminary data in the summer of that year. To other Forest Service workers in this region who foresaw and emphasized the need for the data obtained, some years before the project was formulated, acknowledgment is due, including especially the late L. G. Hornby.

the northern Rocky Mountain region is the yet-unsolved problem basic to the successful practice of forestry.

Between 1910 and 1925 many studies were made of temperature inversions in relation to frost belts and frost-free belts in fruit-growing regions. Young (*24*)[3] found in California that nocturnal temperature gradients below an inversion were steeper on steep slopes than on gentle ones. Young (*25*) also found the highest minimum temperatures at 200 to 1,500 feet above the valley floor in California and Oregon. Inversions as great as 24° F. were measured in a vertical distance of 250 feet. The nocturnal temperature gradient was steeper in the free air over the valley than along the slopes. Gordon (*7*) found the growing season to be fully a month longer on some of the hillside exposures along the Salt River valley of Arizona than in the valley bottom because of this nocturnal layering of cold and warm air. Pierce (*18*) likewise found thermal belts responsible for a noticeable differential in time of leafing of forest trees between valley bottoms and the hillsides above, and Cox (*3*) showed nocturnal temperature inversions in North Carolina to be most frequent in May and November and least frequent in August, with greatest magnitude in April and November and least in August during the time of his comprehensive study.

Relative humidity was found by Bauer (*2*) to average less at high elevations than at low in the Santa Monica mountains. During the summer of 1932 it averaged 45 percent at 2,819 feet and 72 percent at 747 feet shortly before noon.

Precipitation tends to increase with altitude up to a "zone of maximum precipitation" and to decrease above this zone, the differential between altitudes being greater during the wet season than during the dry. Alter (*1*) reported annual precipitation on the west front of the Wasatch Mountains to be twice as great at 8,000 feet as at 4,250 feet. Price and Evans (*19*), reporting on 20 years of study on the west front of the Wasatch plateau, find winter precipitation to be almost three times as great at 8,850 feet as at 5,575 feet, and summer precipitation at the higher elevation to be less than twice as great as at the lower. The amount of precipitation decreased above 8,850 feet. Hann wrote, as quoted by Henry (*8*)—

> The altitude of the zone of maximum precipitation depends upon the average condition of saturation of the ascending air masses, their relative humidity, and the temperature at which saturation begins. In winter great relative humidity and low temperature together unite to depress the level of the zone of maximum precipitation; in summer dry air and high temperatures elevate it * * *. The less the total precipitation, the less its increase with altitude.

Altitudinal variations of forest-fire danger factors have not been generally recorded. Larsen (*16*) determined the length of fire season in North Idaho at different elevations. His elevation classes were, however, largely identified by vegetation type zones rather than by meteorological data. He found the possible length of fire season to vary from 150 days in the ponderosa pine type to 76 days in the subalpine type. He considered the fire season open in the spring when mean temperature rose to 50° F. and closed in the fall when the mean dropped below that value.

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[3] Italic numbers in parentheses refer to Literature Cited, p. 37.

Some early determinations of litter moisture on north and south slopes at 4,000, 5,000, 6,000, and 7,000 feet on the Feather River Experimental Forest were reported on by Show (*21*) from samples collected but once a day. On north slopes litter was found to be driest at 6,000 feet and wettest at 4,000; on south slopes, driest at 7,000 and wettest at 6,000 feet.

The most significant phenomenon contributing to fire-danger variations as influenced by altitude is the nightly temperature inversion produced by air drainage, a complex process quite thoroughly described by Humphreys (*10*) and Marvin (*17*). Briefly, after an in-

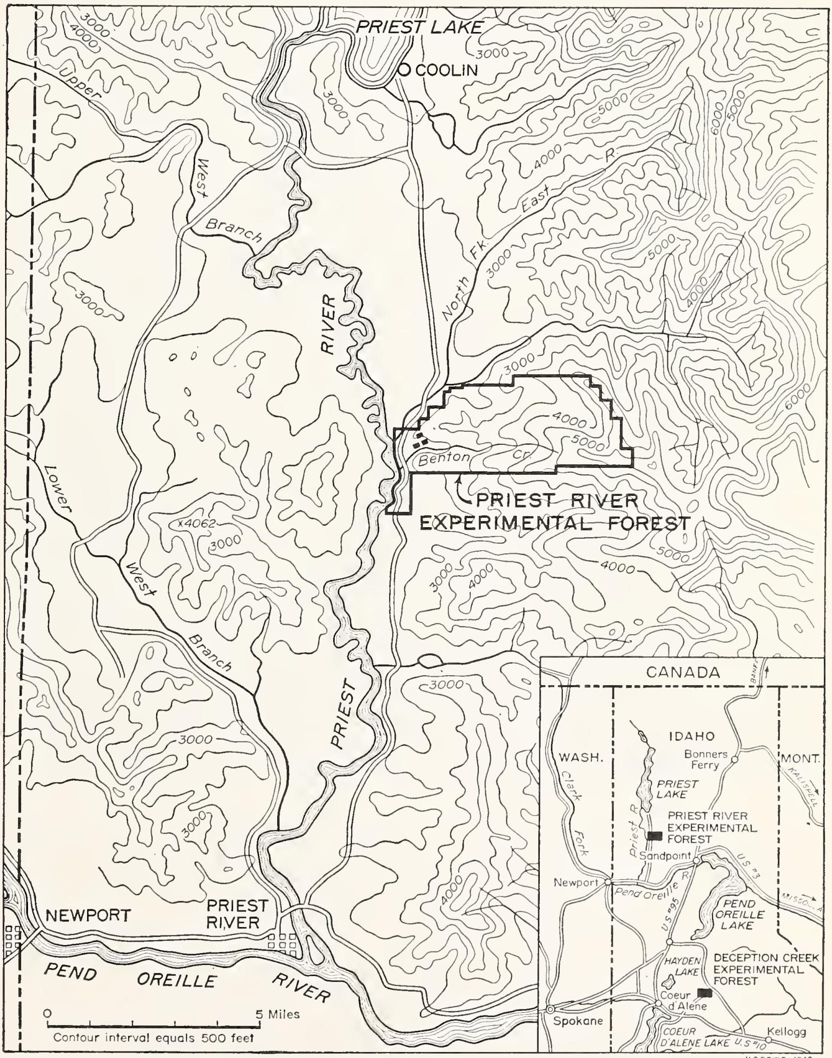

FIGURE 1.—Map of lower Priest River Valley showing the nature of topography on and surrounding the Priest River Experimental Forest. Contour interval equals 500 feet.

version has formed over a valley, a river of cold air occupies the atmospheric stratum near the valley floor. Temperature will be found to increase, usually rapidly, from the valley floor to the top of the inversion layer and decrease at a normal rate with increasing elevation above the inversion layer. Where slopes extend into or through the top of the inversion a thermal belt exists, or an altitudinal zone in which air at night is warmer than that either above or below the belt.

The present circular details the first known systematic study of the daily variations of forest-fire behavior as influenced by altitude and exposure, in which continuous, 24-hour records were obtained.

DESCRIPTION OF STUDY AREA

The Priest River Experimental Forest, within which this study was conducted, lies on the east side of Priest River Valley about 12 miles from its southern extremity, in timbered, mountainous northern Idaho about 60 miles northeast of Spokane, Wash. (fig. 1). The valley extends roughly 70 miles almost due north and south from the Pend Oreille River into Canada. The valley bottom throughout the lower half of its length is 2,000 to 3,000 feet in elevation and 4 to 7 miles wide, with ridges rising to 5,000 and 6,000 feet on each side and about 20 miles apart. Priest Lake occupies most of the valley bottom for about 30 miles, starting 9 miles north of the experimental forest.

To the north of the experimental forest the valley is predominately covered with green timber, but to the south logging and fire have denuded most of the valley bottom and the mountains to the west. The denuded areas are now in farms or in the process of vegetative reestablishment. The Freeman Lake forest fire (*11*) swept across the mountains and the valley south of the experimental forest in 1931, burning over 22,000 acres between 10 a. m. and 10 p. m. of one day.

Two timbered drainages are embraced within the experimental forest, rising from 2,300 feet elevation at the west boundary to 5,800 feet at the east. The study was conducted along the southernmost ridge.

The climate is characteristically warm and dry in summer and wet in winter. More than 41 percent of the mean annual precipitation of 28.51 inches (record based on 25 years) falls during 3 months of the year (November, December, and January); the most dangerous fire months, July and August, together receive but 6.5 percent.

The copious winter precipitation saturates the soil which feeds the forest, resulting in abundant forest growth and abundant fuels, which the dry summers, aided by prevailing winds from arid eastern Washington, desiccate excessively. The result is a combination of fuel abundance and dryness that is equalled in few places in the world.

METHODS AND INSTRUMENTS USED

Inflammability Stations and Equipment

In the summer of 1934 six paired sites for inflammability stations were cleared on north and south sides of a ridge rising from west to east out of Priest River Valley, in each case within 50 feet eleva-

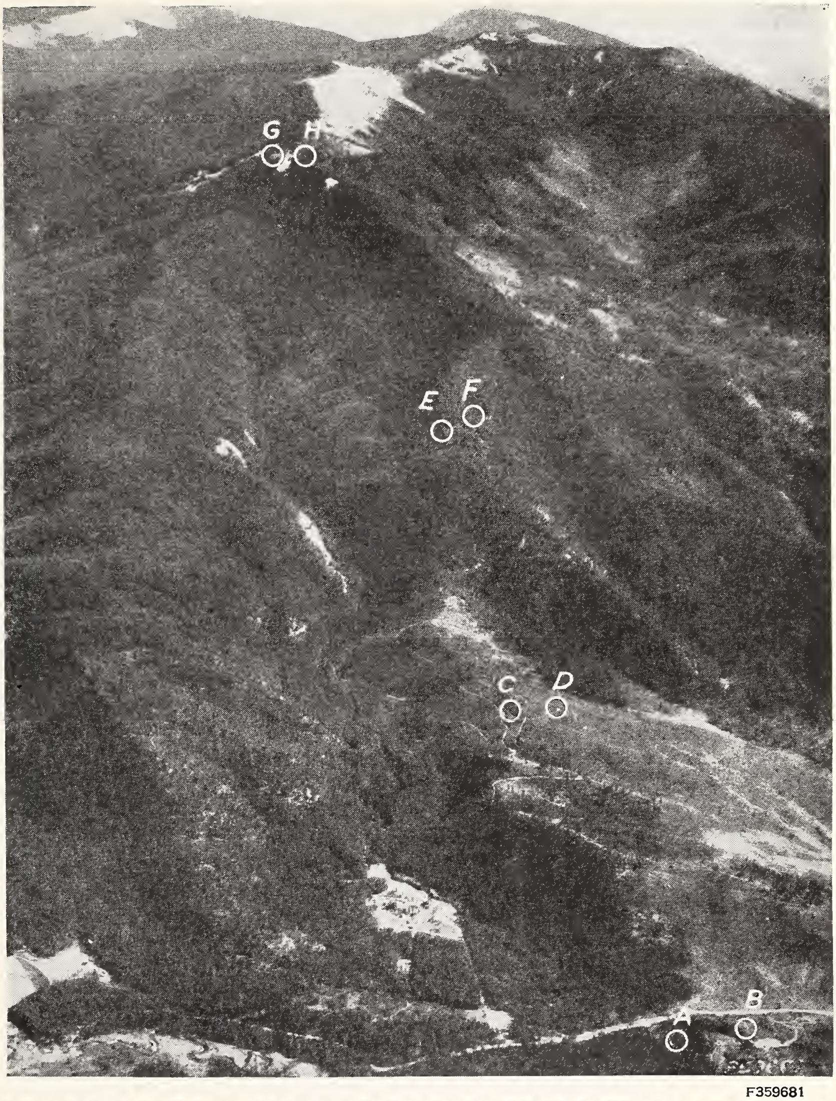

FIGURE 2.—Aerial view of Priest River Experimental Forest with locations of weather and inflammability stations. The top of the view is east: *A*, partly timbered and *B*, fully exposed, 2,300-foot elevation; C, north aspect and *D*, south aspect, 2,700 feet; *E*, north aspect and *F*, south aspect, 3,800 feet; *G*, north aspect and *H*, south aspect, 5,500 feet. (Photo by 116th Photo Section, Washington National Guard.)

tion of the top of the ridge (fig. 2). One pair (*G*, *H*) were located at 5,500 feet—the south-aspect station in a natural opening in scattered subalpine trees, and the north-aspect station in an artificial clearing of about 1 acre. A second pair (*E*, *F*) were placed at 3,800 feet elevation, both in artificial clearings of about 0.25 acre. The third pair of stations (*C*. *D*) were located in a brush field at 2,700

feet elevation. Since all instruments were of such a nature or so placed that the surrounding brush should not affect them, these clearings were made just slightly larger than the station enclosures (20 by 20 feet).

To tie the results of this altitude and aspect study to those of a previous project devoted to the effect of timber stand density on fire danger (*12*), additional instruments were added to two existing inflammability stations at the 2,300-foot elevation to make them part of the study. These stations, on a level bench in the valley bottom, about 700 feet apart (fig. 2, *A* and *B*), differ only in their timber cover, one being in the open and fully exposed to sun and wind, the other under a partial timber canopy. The residual timber stand on the latter consists of western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*). Haig[4] made light determinations at the instrument locations beneath this partial canopy with three instruments, a Clements photometer, Shirley thermopile, and Livingston black and white spheres. His results were 24, 23, and 26 percent, respectively, or an average of 24.3 percent of full sunlight.

The only practical means of obtaining simultaneous periodic measurements at these eight widely separated stations throughout the day and night was with recording instruments. Of the records obtained at each station, namely, temperature, relative humidity, duff moisture, ½-inch-wood moisture, wind movement, precipitation, and duff-surface maximum temperature, the first five were continuously recorded. Precipitation was measured after each storm and duff-surface maximum temperature observed twice a week.

Temperature and humidity recorders have long been available. The invention in 1933 of a combined fuel-moisture and wind recorder made possible continuous records (fig. 3) of the other two most important factors contributing to the daily cycle of fire behavior. The new instrument (fig. 4), designed by H. T. Gisborne in collaboration with M. E. Dunlap of the Forest Products Laboratory, Madison, Wis., records the moisture content of duff and of ½-inch wood cylinders, and every fifth mile of wind which passes a standard 3-cup anemometer.

The measurement of duff or the surface litter of dead needles and twigs blanketing the forest floor and constituting the most widespread carrier of fires in the region, is accomplished by application of the principle employed in the duff hygrometer earlier perfected by Gisborne and Dunlap (*5, p. 58*). When the instrument is properly calibrated, duff moisture is recorded to an accuracy of ±1 percent below 15 percent and with decreasing accuracy up to 35 to 50 percent, the maximum measurable by this principle.

The ½-inch wood cylinders or dowels of clear ponderosa pine sapwood ½-inch in diameter and 18 inches long represent small branch wood, a second important carrier of fire. These cylinders are exposed horizontally 10 inches from the ground, representing a typical exposure of branch wood not in contact with the ground. Half-inch wood moisture was measured and recorded to an accuracy of ±1 percent.

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[4] HAIG, I. T. CERTAIN FACTORS CONCERNING INITIAL SEEDLING ESTABLISHMENT IN WESTERN WHITE PINE STANDS. 1935. [Unpublished doctor's dissertation. Copies on file at Yale Univ., School of Forestry, New Haven, Conn., and North. Rocky Mountain Forest and Range Expt. Sta., Missoula, Mont.]

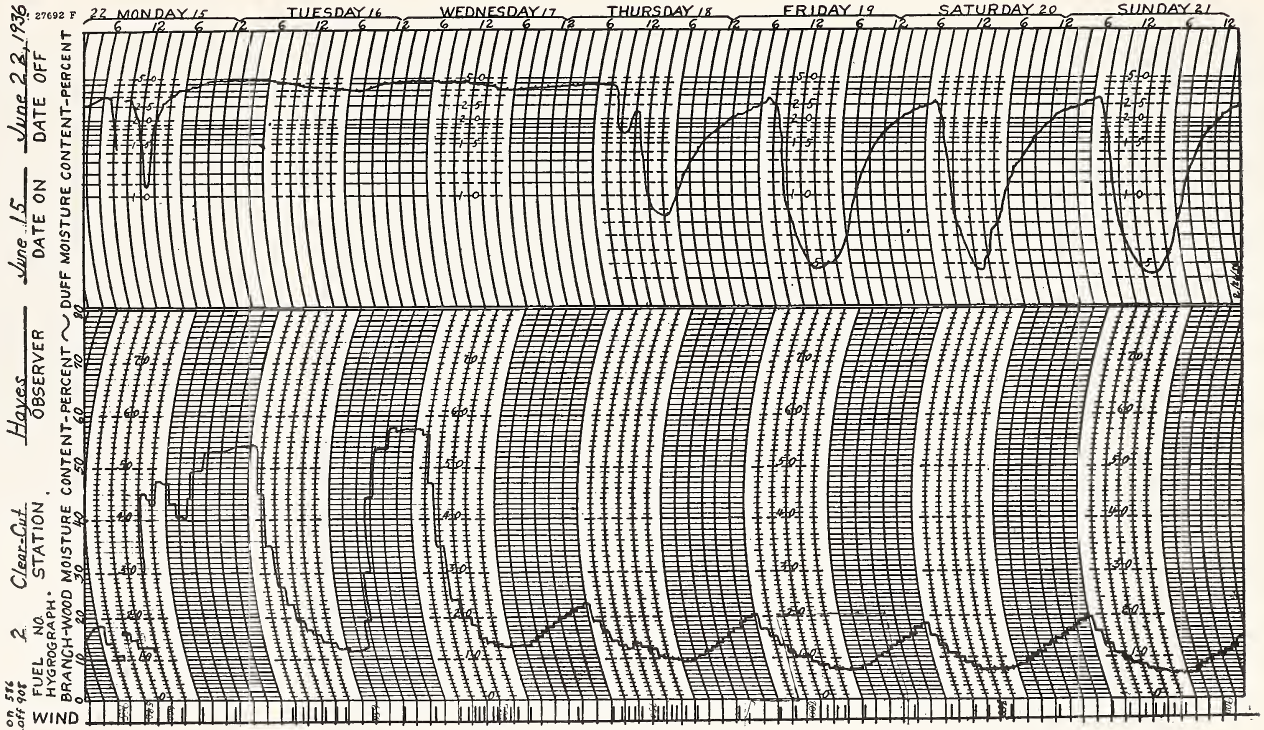

FIGURE 3.—An anemohygrograph chart showing: Top, fluctuations in moisture content of duff (forest litter); lower half of chart, moisture content of ½-inch branch wood; near bottom margin, every 5 miles of wind. Precipitation of 0.03 inch fell June 14, 0.19 inch June 15, 0.10 inch June 16, 0.29 inch June 17, and a trace June 18. The "steps" in the pen traces occur once each hour when a buzzer circuit is closed for 10 to 20 seconds to reduce friction between the pens and chart.

Wind movement was recorded to the accuracy of the respective anemometers. All anemometers were compared and correction factors used when necessary to make the results comparable.

Air temperature and relative humidity were recorded by hygrothermographs placed in an instrument shelter 4½ feet above the ground.

Precipitation was first measured, during the 1935 and 1936 seasons, with Forest Service rain gages in standard exposure with the catchment funnels horizontal and 2 feet above ground. There proved to be large differences in wind velocity between stations, however, and since Koschmeider (*15*) and others have shown that the percent of actual rainfall caught by an open, exposed rain gage varies inversely with wind velocity, it was felt that the rainfall catches were not comparable between stations. Therefore, in the spring of 1937, six special gages were designed to be placed in pits at the 2,700-, 3,800-, and 5,500-foot stations, surrounded by 6- by 6-foot splash-preventing mats after the procedure described by Koschmeider. In order that the orifice of the vertical gage could be set flush with the surface of the sloping hillside, each orifice had to be cut at an angle equal to the slope where used. Through 1937 and 1938, precipitation records were taken at the six slope stations with both types of gage.

Duff-surface maximum temperature was obtained in 1935 and 1936 by exposing a standard maximum thermometer about one-fourth of an inch under the surface of each duff bed. Extreme care had to be exercised with this method to insure comparable exposure of all thermometers, however, and to keep them comparably exposed from one observation to the next. Beginning in 1937 the thermometers have been placed on top of the duff and covered by two layers of burlap. Tests have shown that this method produces results comparable to proper exposure under ¼-inch of duff and insures uniformity of exposure at all stations.

Complete equipment at each of the eight stations, in addition to the instrument shelter (type R–1), consisted of the following:

1 hygrothermograph.
1 anemohygrograph, complete with 3-cup anemometer.
1 Forest Service rain gage with support.
1 beveled orifice rain gage (1937 and 1938 only).
1 maximum thermometer (at duff surface).
1 fan psychrometer per pair of stations.

Practices Followed To Assure Accuracy of Data

Numerous precautions are essential in research of this type to assure equal accuracy of data in field and office. Previous work had shown, for example, that even the most expensive hygrographs require extremely careful periodic checking and resetting, that standard anemometers do not always agree, and that even the best clock-operated mechanisms occasionally gain or lose time.

Temperature recorders were checked several times during the season with maximum and minimum thermometers.

Humidity recorders were checked before each season's use in a specially constructed humidity and temperature-controlled chamber for accuracy of calibration.

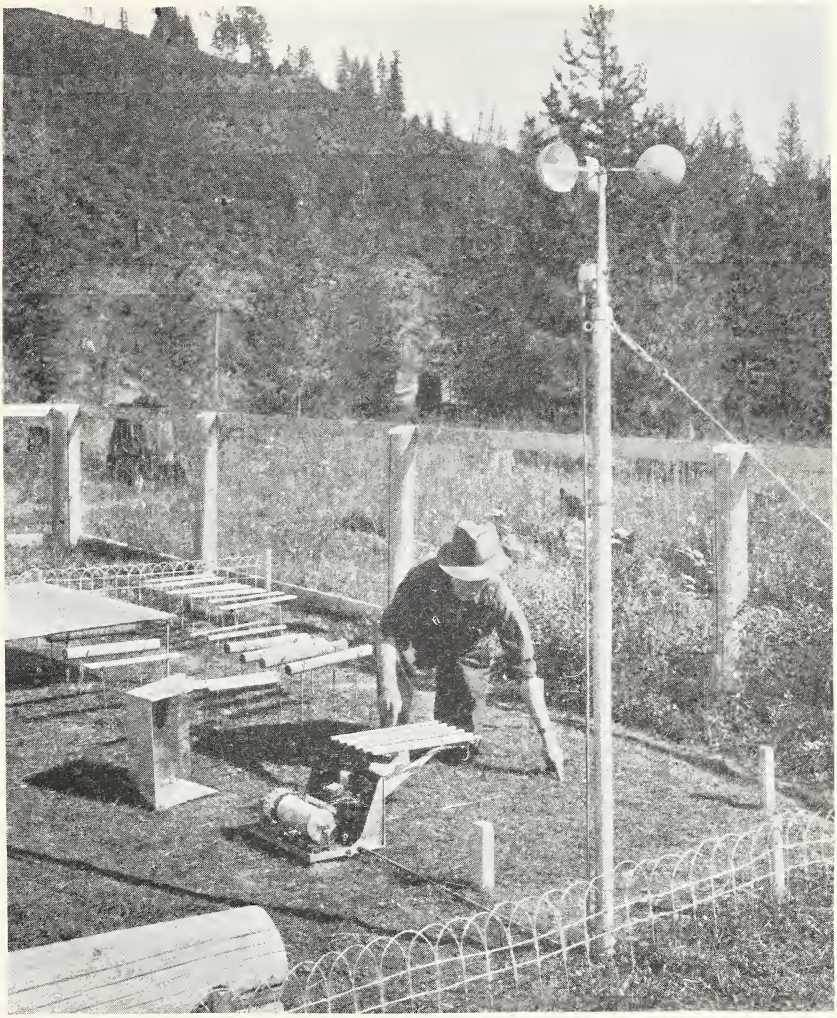
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FIGURE 4.—Anemohygrograph with cover removed. The pen on the left is actuated by a rattan element in a perforated spike under the man's left hand. The sensitive part is under a quarter of an inch of duff and expands or contracts with changes in the humidity within the duff layer. The middle pen records the moisture content of the six wood cylinders to which the man is pointing with his right hand. The pen on the right is actuated mechanically by the anemometer.

The duff-moisture recorders were calibrated at the beginning of each field season by the methods described by Kachin and Gisborne (*14*). Checks throughout the field season were obtained every time rains raised duff moisture to 50 percent or higher. Checks at low-moisture contents were obtained by exposing recently calibrated duff hygrometers beside the recording instrument or by collecting and

oven drying samples of the duff in which the instrument was exposed.

The wood-moisture recorders were carefully calibrated between field seasons and the calibration checked over the instrument's entire range two or three times during each season of use.

Anemometers were checked annually by exposure side by side, 24 inches from spindle to spindle, with the instrument line at right angles to the prevailing winds. From frequent, simultaneous readings of all the dials, comparative movements were obtained and a correction factor was determined for each instrument. Owing to lack of a wind tunnel, calibration curves were not attempted for all velocities. The more sensitive instruments were placed at the least windy stations in order to reveal differences between stations most dependably.

In addition to these precautions, all stations were inspected twice weekly by a detailed and systematic procedure. This included a check of temperature recorders; check against a fan psychrometer of the humidity recorders—each check consisting of three relative-humidity determinations made over a period of 15 to 30 minutes; removal and weighing of the cylinders from the wood-moisture recorders; and a careful check of all the clock-operated mechanisms.

Precautions were likewise taken in assembling and compiling the data from the instrument charts. No chart was compiled until checked, corrected, and approved by the field operator. To insure accuracy of compilation, the bihourly data from each chart were tabulated independently by two compilers. The two tabulations were then compared and all discrepancies traced and corrected. Totals and means were checked by adding both down and across. Medians were computed separately by two individuals and checked.

RESULTS OF DAILY MEASUREMENTS

Since the purpose here is to study diurnal trends at various altitudes on north and south slopes, such significant seasonal trends as were noted will be treated elsewhere. As the continuously settled weather of August is conducive to sustained high fire danger, the average day of this month is used frequently for illustration. The average of four Augusts, 1935–38, is used to illustrate temperature, relative humidity, and ½-inch-wood moisture, while that of the three Augusts of 1936–38 is used to illustrate duff moisture and wind velocity.[5]

The averages used, unless otherwise specified, are medians. The median has proved markedly superior to the mean in revealing practical differences of the type being sought by this research although means are sometimes necessary for the determination of statistical significance.

Temperature

Air temperature is a direct control of both relative humidity and fuel moisture content, and also exerts a very important control on fire behavior distribution through the inversions set up in the night

[5] Duff-moisture measurements in 1935 did not meet the standards of accuracy of the study (± 1 percent below 15 percent). In 1935 only every 10 miles of wind was recorded.

period, as already described. This temperature inversion at midaltitudes brings about corresponding inversions of relative humidity and fuel moistures, creating a basic altitude-fire-behavior relationship that has not been recognized in the past by fire-research investigators, by fire fighters, or by fire-control planners. Temperature is therefore not only a direct control of fire behavior at any time or place but also a major factor in altitudinal zoning of fire behavior.

The nocturnal inversions are typically fair-weather phenomena. They are frequently present during unsettled weather but attain their best development during the long periods of dry, hot, settled, typical fire weather of midsummer. Consequently during periods when burning conditions are most dangerous, nocturnal inversions generally attain their greatest magnitude and the altitudinal zoning of fire behavior is most marked.

The frequency of inversion occurrence over the study area is evident in table 1, which shows that it was warmer at 3,800 feet[6] than on the valley bottom on almost 9 nights out of every 10 during May and June, 9½ nights out of 10 in July and September, and during 4 successive Augusts every night but one. It is therefore obvious that inversion occurrence is typical of this mountainous region and not just an occasional phenomenon.

TABLE 1.—*Frequency and magnitude of nocturnal temperature inversions over Priest River Experimental Forest, 1935–38*

FREQUENCY

Year	May	June	July	August	September
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
1935	100	97	94	100	100
1936	83	80	90	100	91
1937	81	90	100	97	93
1938	96	90	100	100	100
4-year average	90	89	96	99	96

MEDIAN MAGNITUDE

Year	May	June	July	August	September
	°F.	*°F.*	*°F.*	*°F.*	*°F.*
1935	12.0	9.0	13.0	18.0	18.5
1936	12.0	4.5	16.0	19.0	12.0
1937	9.0	7.0	13.0	17.0	16.0
1938	8.0	9.0	16.0	19.0	19.5
4-year median	9.0	8.0	15.0	18.0	17.0

On the median or typical night of May and June, the 3,800-foot elevation was the warmer by 9° F. and 8°, respectively, and during July to September it was the warmer by 15° to 18°. These are material differences, obviously sufficient to affect relative humidity, fuel moisture, and fire behavior, yet they have seldom been recognized in planning either the location of fire-control facilities or the dispatching of men for nighttime fire fighting.

During May and June, when the average inversion magnitude is but 8°F. or 9° and fire danger is moderate, extra precautions in

[6] The inversion magnitudes were determined from the temperature difference between 2,300-foot and 3,800 foot elevation. In July 1936 minimum thermometers exposed every 300 feet in elevation from 2,300 to 5,500 feet revealed the top of the inversion to be usually 400 to 700 feet below 3,800. Therefore, the magnitude values are conservative.

the thermal belt may not be warranted. During July, August, and September when both the frequency and magnitude of the inversion are near the maxima and fire danger is high, the greater 24-hour sustained danger that will be shown to exist in the thermal belt should be considered by fire-control tactics and in placing both lookouts and smoke chasers.

The nocturnal temperature inversion, attaining a maximum magnitude of 17° F. to 19° about 5 a. m., is clearly evident in figure 5 which illustrates the daily cycle of temperatures along south and north slopes, respectively, on the median day of August 1935–38. This chart has an altitudinal range from 5,500 to 2,300 feet. At 2,300 feet data were not obtained from north and south slopes but only from the level valley bottom. Consequently, the base-elevation temperatures in both parts of figure 5 were obtained from the fully exposed valley bottom station and are identical.

A clear conception of this and similar charts to follow involves the recognition of certain altitudinal zones and time periods. The data reveal three distinguishable altitudinal zones. These are the thermal belt, clearly evident in figure 5 as extending roughly from 3,000 to 4,000 feet and persisting from 10 p. m. to as late as 7:30 a. m.; a high zone, lying above this thermal belt; and a low zone, lying below.

There are four significant time periods: A night period from about 10 p. m. to about 6 a. m., when the thermal belt is most distinct; a morning transition period from 6 to 10 a. m., when the belt is being disrupted; a day period from 10 a. m. to 6 p. m., when surface heating and convection produce a normal temperature gradient with altitude; and an evening transition period from 6 to 10 p. m., when air drainage is forming the thermal belt at midaltitudes.

The temperature characteristics of the altitudinal zones are as follows:

The thermal belt is the zone of maximum temperature at night. It has a small daily temperature range and the highest mean temperature of any altitudinal zone.

The high zone has a small daily temperature range and is at all times cooler than the thermal belt except for a short time during the morning transition period on north slopes.

In the low zone daily temperature has a greater range than in either of the other zones.

The temperature characteristics of the time periods are also quite distinct. The night period is characterized by a temperature gradient rising rapidly (as much as 18° F. in 1,000 feet) from the valley floor, reaching a maximum in the thermal belt, then falling slowly with increasing altitude above the maximum. The morning transition period is characterized by dispersion of the inversion and a thorough convectional mixing of the air, so that by 9 a. m. normal daytime gradients are becoming established. During the day period temperatures decrease with a more or less uniform gradient from valley bottom to mountain top, amounting to about 14° F. in 3,000 feet between 2 and 4 p. m. The day period gradient is upset by radiational losses following sunset. Although the evening transition is slower than the morning, it is definitely accomplished by 10 p. m.

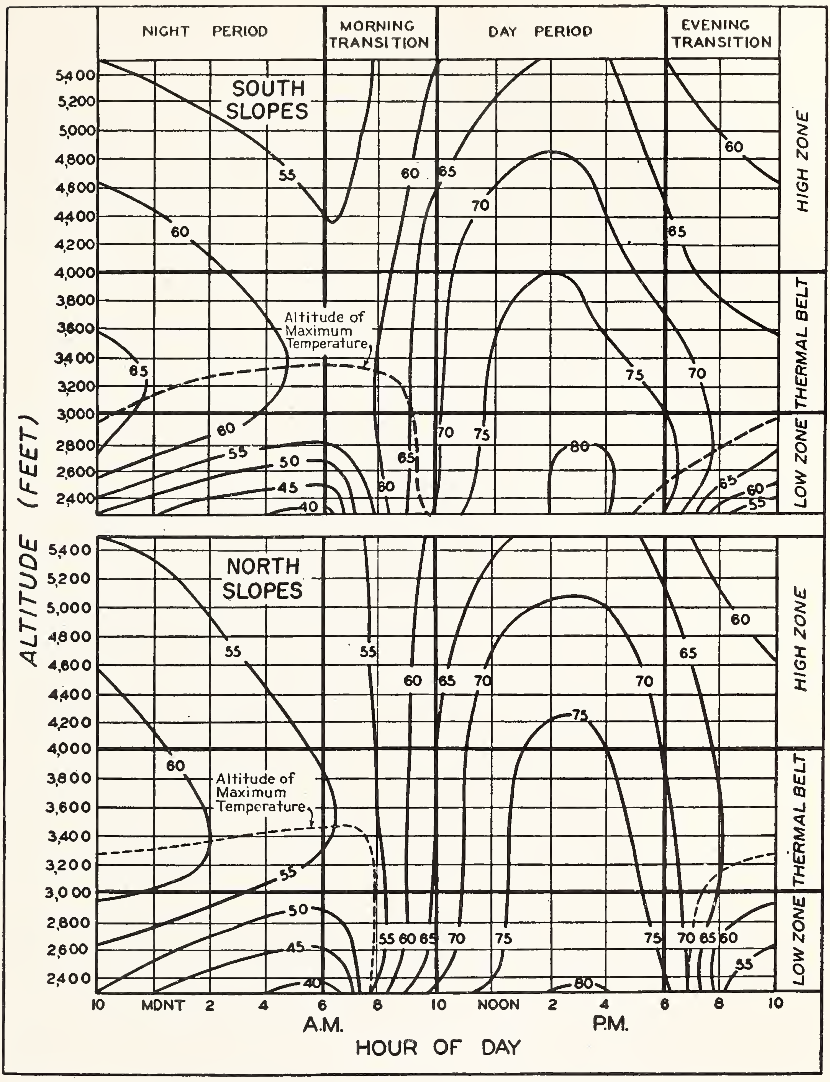

FIGURE 5.—Isograms showing the daily cycle of temperatures in degrees Fahrenheit for the median day of August 1935–38, at various altitudes on south and north slopes, Priest River Experimental Forest.

Since higher temperatures contribute in several ways to more rapid spread of fire, these altitudinal zone and time characteristics are basic to both fire-fighting tactics and fire-control planning. While the records of high daytime temperatures accord with the wide-spread opinion that fires in general spread faster during the day and slower at night, and faster in the valley bottoms than on the mountain tops, the night-period and morning-period temperatures make it clear that this common opinion should not be accepted as applicable to all elevations at all hours of the day and night. In other

words, it should be recognized that the level of highest danger for which high temperatures are in part responsible mounts the slopes following sunset, comes to rest through the night some 700 to 1,700 feet above the valley floor, and returns toward the foot of the mountain shortly after sunrise. By 9 a. m., practically uniform temperatures obtain at all elevations and on both aspects. Not until then does the common concept of fire behavior distribution become dependable. It should be recognized that the height of the thermal belt, where present, will differ with different localities depending upon height of valley bottom, height of mountains above, steepness of slopes, and other factors, and therefore will not be 700 to 1,700 feet above the valley bottom in all mountainous regions.

In fighting fires it is obvious that advantage should be taken of the greater nightly cooling in the valley bottoms by concentrating effort at night in the thermal belt.

The temperature-altitude relationships discussed are true for both south and north aspects but on the warmer south slopes fires will burn more readily. Fire-control planners therefore assign to similar fuels more rapid rates of spread on south than on north slopes. Temperature differences between aspects are not the same at all altitudes, however, for the higher the altitude, the more do north aspects tend to be as warm as south (fig. 6); in fact, at 5,500 feet the north side was slightly warmer for 15 hours of the median day of August, and even at 3,800 feet the north side was the warmer for 8 hours of the most critical burning period of the day. Thus whereas the mean daily temperature on south aspects on the median day of August 1935–38 was 4.3° F. warmer at 2,700 feet, it was only 1.1° warmer at 3,800 feet and was 0.7° cooler at 5,500 feet. These differences show that the ameliorating effect of the north aspect is not constant at all altitudes. While it is probably true that a body of fuel on a north slope is always less dangerous than a similar body of fuel on the south slope, rates of spread will be more nearly the same for north and south aspects at high elevations than at low.

The temperature difference between aspects varies not only with altitude but also with time. Figure 6 shows that north slopes tend to be warmer than south slopes during the last half of the day period, the most critical period for fires, whereas south slopes have the greatest excess of warmth over north during the morning and evening transition periods.

Relative Humidity

Relative humidity is usually the most effective of the meteorological determinants of fuel-moisture content during periods without frequent rains. In fact, some fire-control men have considered it alone as a highly significant index of burning conditions (*9*, *20*), and Jemison (*13*) found that relative humidity and air temperature together accounted for 97 percent of the variations in 4 p. m. duff moisture content from day to day.

The relative humidity at any time is determined by the current air temperature and the temperature of the dew point. Dew points were found to decrease with increasing altitude at a nearly constant

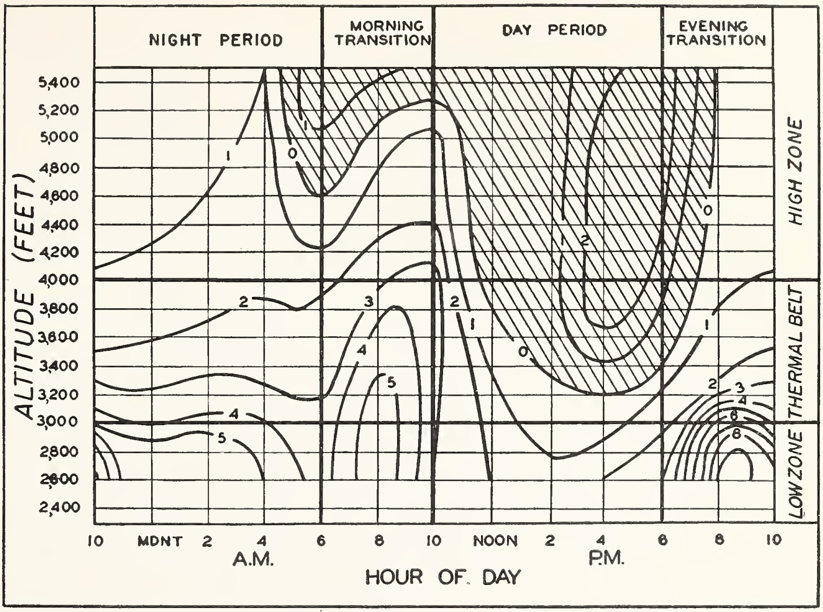

FIGURE 6.—Isograms showing the daily cycle of temperature differences between north and south aspects, for the median day of August 1935–38. The isograms are discontinued as they approach the valley bottom where north and south aspects do not exist. On shaded portions of the chart north-aspect values are greater; on unshaded portions, south-aspect values. Priest River Experimental Forest.

gradient at any time of day. Consequently, relative humidity is lower in the high zone at a given prevailing temperature than in the thermal belt or low zone with the same temperature, and lower in the thermal belt than in the low zone when prevailing temperatures are the same.

Dew point remains relatively constant at any altitude during the evening transition and night periods, but increases remarkably during the morning transition period at all altitudes to a maximum between 10 a. m., and noon, and declines again through the day period. The increase of dew point in the thermal belt and high zones during the morning transition period is caused by the moist air from the atmospheric strata near the valley floor, which is carried up the slopes by the morning convectional winds. The moist air passes above the mountaintops between 10 a. m., and noon, and the dew point declines. In the low zone, near the valley floor, the dew point is increased during the morning hours by direct addition of moisture to the air when the morning sun evaporates the nightly deposits of dew. After the dew is evaporated and the moist air carried away by convection, the dew point declines. This morning movement of moist air from the low zone up the slopes and aloft into the free air above the mountains agrees with Schell's [7] findings on Mount Washington.

[7] SCHELL, IRVING I. DIFFERENCES BETWEEN TEMPERATURES, HUMIDITIES, AND WINDS ON THE WHITE MOUNTAINS AND IN THE FREE AIR. *In* Amer. Geophys. Union Trans. 15: 118–124, illus. 1934. [Mimeographed.]

The daily cycle of relative humidity at different altitudes, resulting from the temperature cycles illustrated in figure 5, and modified by the dew-point changes just discussed, is shown in figure 7. Figure 5 showed the thermal belt to be a zone of sustained high temperature. Figure 7 now shows it to be a zone of sustained low humidity.

The commonly accepted opinion that the valley bottom and low slopes have the greatest fire danger at all times is not verified by this study of relative humidity. Minimum relative humidity for any hour from 10 a. m. until about 5 p. m. remained near the valley floor, but figure 7 shows that along south slopes relative humidity was lower in the thermal belt than on the valley bottom from 5 p. m. to about 10 a. m., 17 hours out of 24, on the typical August day; and during the remaining 7 hours of the day period the relative humidity in the thermal belt was never more than 4 percent higher than in the low zone. In contrast, relative humidity in the thermal belt was 50 percent less than at the valley bottom station for 8 hours of the day. Even the high zone averaged lower humidity than the low zone from 7 p. m. until 9 a. m., a period of 14 hours, on south slopes, indicating the presence of greater humidity danger in the high zone than in the low for this period. The high zone, like the thermal belt, registered a small daily fluctuation but averaged 0 to 6 percent higher humidity than the thermal belt at all hours.

Only small differences appear between thermal-belt and high-zone humidities on north slopes. The thermal belt was less humid than the high zone from 10 p. m. until 5 a. m. and again from 1:30 p. m. to 5 p. m. On two occasions during the day, centered during the morning and evening transition periods, the high zone became less humid than the thermal belt. This occurrence is attributed, in part at least, to the high timber around the thermal-belt station at 3,800 feet, which during the morning transition periods keeps the station location in shade ½ to 2¼ hours later than other north-aspect stations and hinders the passing of the moist air that is carried aloft from the valley bottom during this period. During the evening transition period the thermal-belt north station is shaded 2 hours earlier than is the high zone and consequently starts cooling first, with an accompanying rise in humidity. Despite this influence of forest cover, the 24-hour average humidity in the two zones differed but 1 percent.

It is clear that the low zone is relatively safer on north slopes than on south. If the immediate valley bottom is disregarded, and it certainly cannot be considered representative of a north aspect, the low zone was more humid than the thermal belt for all hours except a short period from 10 a. m. until shortly after noon—almost 22 hours; and it was more humid than the high zone for 18 hours, from 4:30 p. m. until 10:30 a. m. Even during the day period, when low south slopes were less humid than the higher zones, the north-side low zone was more humid than the thermal belt and lower part of the high zone. Considering the long periods of the 24 hours when relative humidity above 3,000 feet on north slopes was less than that below, and considering the small humidity differences between all altitudes during the day period, it is evident that north-facing areas within the low zone will be the easiest on which to control fire, and that little difference will exist between the thermal belt and high zone provided fuels, degree of slope, and other constants are comparable.

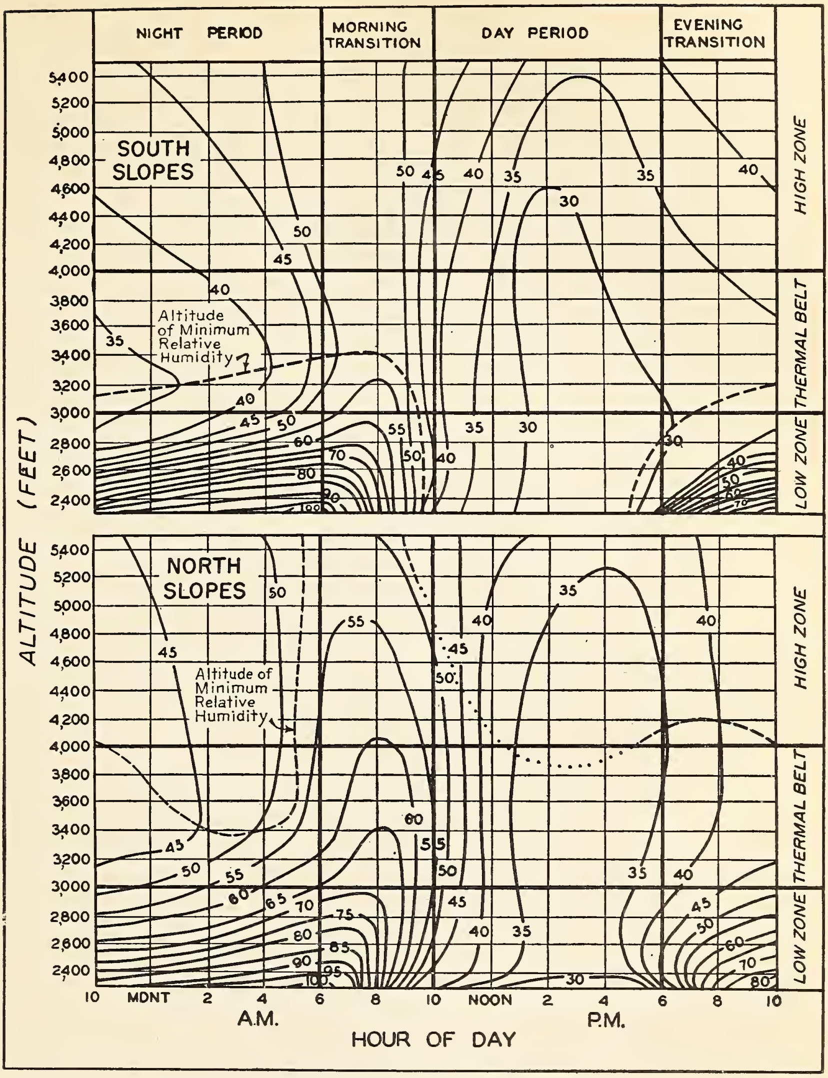

FIGURE 7.—Isograms showing the daily cycle of relative humidity for the median day of August 1935–38, at various altitudes on south and north slopes. The dotted section of the broken line in the lower isogram represents the altitude of minimum humidity on true north slopes only. The valley bottom at a 2,300-foot elevation was less humid than north slopes at any elevation from 9:30 a. m., to almost 6 p. m.

Figure 8, showing the relative-humidity differences between aspects, further verifies the indication gained from temperature differences that the higher the altitude, the more north aspects tend to be like south. The daily mean humidity on north slopes was greater than on south by 10.3 percent at 2,700 feet, and 5.8 percent at 3,800 feet, while at 5,500 feet the north-aspect humidity was less than the

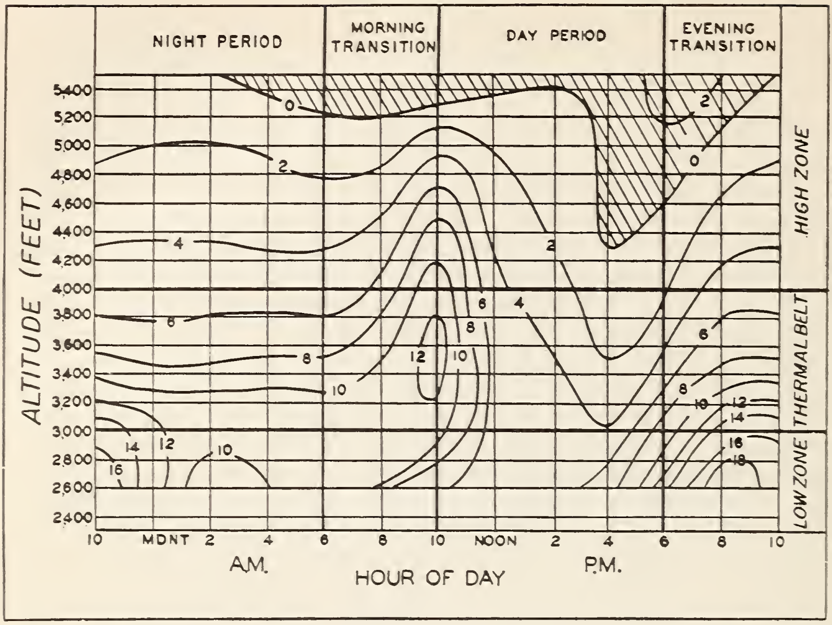

FIGURE 8.—Isograms showing the daily cycle of differences in relative humidity between north and south aspects at various altitudes, for the median day of August 1935–38. The isograms are discontinued near the valley bottom where north and south aspects cease to exist. On unshaded portions of the chart north-aspect values are greater; on shaded portions south-aspect values. Priest River Experimental Forest.

south-aspect by 0.8 percent. Despite the large humidity difference between aspects in the thermal belt during the morning transition period, which has already been attributed to forest cover, the average difference at 3,800 feet was but slightly over half as great as at 2,700 feet.

Humidity differences between aspects, like temperature differences, were least during the day period and greatest, especially at low elevations, during the morning and evening transition periods.

Temperature and relative humidity are clearly the major fair-weather controls of fuel moisture content. On sites fully exposed to the sun, however, and especially south aspects, both of these factors are subordinate to insolation as controls of duff moisture during the midpart of clear days.

Insolation

When this study was originated, insolation was not included as one of the variables to be measured. The first year's records demonstrated, however, that midday duff moisture contents, especially on the sites most exposed to the sun were not being determined by air temperature and relative humidity alone. In seasonal trend of daily records, minimum ½-inch-wood moisture followed closely the minimum relative humidity and maximum temperature, but minimum duff moisture did not. On south slopes, where insolation is strongest,

the same minimum duff moisture was recorded, within limits of instrumental variation, on all clear days from May to August. Some days the air temperature would be 70° F. and relative humidity 30 percent; on other days the temperature was over 95° and relative humidity under 15 percent. Despite such differences, the minimum duff moisture at any south-aspect station would vary less than ± 1 percent from one clear day to the next. This could be attributed only to insolation, which had previously been recognized by Gast and Stickel (*4*) to have an important effect upon duff moisture.

At the fully exposed level station, the dominance of insolation during midday was almost as strong as at south-aspect stations. Seasonal trends of minimum duff moisture showed the same divergence from seasonal trends of temperature and relative humidity; but following heavy rains, duff moisture failed to dry to its fair-weather minimum as rapidly on the level as on south slopes. On north slopes, insolation was a major factor, but more variation occurred in the clear-weather daily minimum duff moisture content and in late season (September–October) the sun's rays fell so obliquely and for so few hours on north slopes that the insolational effect was subordinated to soil moisture and the atmospheric factors.

TABLE 2.—*Comparative maximum duff surface temperatures, August 1936–38, from observations made twice each week, Priest River Experimental Forest*

Situation and elevation (feet)	Median maximum for August				Absolute maximum 1936–38	Slope of duff bed
	1936	1937	1938	Average 1936–38		
	°F.	*°F.*	*°F.*	*°F.*	*°F.*	*Degrees*
Partly timbered: 2,300	96	92	106	97	135	0
North aspect:						
2,700	117	117	122	119	145	18
3,800	130	113	122	121	151	17
5,500	118	104	113	111	145	18
Fully exposed: 2,300	149	134	140	139	167	0
South aspect:						
2,700	150	148	154	150	168	15
3,800	162	160	168	164	181	29
5,500	153	134	150	148	171	21

The relative effectiveness of insolation as a control of midday duff moisture content on the various exposures can be approximated from table 2, which summarizes the duff-surface maximum temperatures for August 1936–38 at all stations. The maximum temperature average for the three south-aspect duff surfaces was 15° F. hotter than the fully exposed level one, 37° hotter than the average for the three north-aspect beds, and 57° hotter than the partly shaded level one. The average maximum duff surface temperature exceeded the average maximum air temperature by the following amounts:

	° F.
Average of 3 south-aspect stations	75.3
Fully exposed valley bottom	53.0
Average of 3 north-aspect stations	36.8
Partly timbered valley bottom	13.5

Insolation influences duff moisture only during the hours of sunshine. At night another minor factor, soil moisture, exerts an influence on the moisture content of light fuels on the ground.

Soil Moisture

Investigators disagree about the influence of soil moisture on duff moisture content. Wright[8] found no significant effect on surface duff in Canada's pine forests but Stickel (*23*), experimenting in the Cranberry Lakes region of New York, obtained a significant correlation between duff moisture and the moisture content of mineral soil beneath a 12-inch layer of organic material, despite the occurrence of rains on an average of every 45 hours during his period of study. These investigators determined duff moisture content during the daytime, however, when solar insolation is active and tending to dominate other controls of duff moisture.

Observations during the present study indicated that soil moisture influenced duff moisture at night. Consequently, the moisture content of the soil was sampled[9] at all stations on eight different dates at approximately 10-day intervals during the latter half of the 1938 season. All observations on September 12 were later discarded because the duff-moisture content at several stations, owing to recent rain, was above 42 percent, or the maximum at which soil moisture and atmospheric humidity could affect it.[10]

Correlation coefficients were computed to determine, for the day that soil moisture was sampled, the degree of relationship existing between soil moisture and maximum duff moisture, and soil moisture and minimum duff moisture. To give a good correlation basis, all data from the partially timbered station and the north-aspect stations were grouped, and likewise all data from the fully exposed valley-bottom station and the south-aspect stations. When the correlation coefficients were tested by table 7.2 in Snedecor (*22*), a highly significant relationship was found between soil moisture content and both maximum and minimum duff moisture for the north-aspect and partly timbered group of data. The south-aspect and fully exposed group showed a significant relationship between soil moisture and maximum duff moisture, but no significance between soil moisture and minimum duff moisture.

Soil moisture is at best only a minor control of duff moisture and is most effective at night when fires are generally least troublesome. In a mountainous country, however, having a thermal belt in which atmospheric factors of fire behavior remain dangerous at night, the moisture content of the soil may make enough difference in duff moisture content to determine whether a fire will burn briskly or merely smolder during the hours of darkness.

All the factors so far discussed as influencing fuel moisture content are fair-weather controls. When rain occurs it dominates all other factors.

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[8] Wright, J. G. Forest-fire hazard research as developed and conducted at the Petawawa Forest Experiment Station. Canad. Dept. Int., Forest Serv., Forest-Fire Hazard Paper 2, 57 pp., illus. 1932. [Mimeographed.]

[9] The top 6 inches of soil were sampled with a geotome. Each sample consisted of 4 cores, 1 from each of the 4 sides of the station enclosures. All pebbles over 3 mm. were screened from the dried samples and their weight subtracted from the moist and oven-dry weights of the sample.

[10] According to tests made by M. E. Dunlap, 42 percent is the maximum duff moisture in equilibrium with 100 percent relative humidity, even when the air temperature is only 50° F.

Precipitation

The precipitation measurements obtained in 1935–36 with Forest Service rain gages in standard exposure (table 3) showed anomalous relationships between aspects, especially at the higher elevations. The mean rainfall catch on the south side was but 91 percent of the north-side catch at 5,500 feet and 83 percent at 3,800 feet, and at the 2,700-foot elevation was 103 percent. The summer storm winds, which were mostly from a southerly direction and therefore stronger on south than on north slopes, were apparently causing a larger proportion of the actual rainfall to be missed by the gages on south than on north slopes.

TABLE 3.—*Precipitation during summers of 1935 and 1936*[1] *as measured by Forest Service rain gages in standard exposure at 8 stations*

Situation and elevation (feet)	1945	1936	Mean	Situation and elevation (feet)	1935	1936	Mean
	Inches	*Inches*	*Inches*		*Inches*	*Inches*	*Inches*
Partly timbered: 2,300	3.20	5.73	4.46	Fully exposed: 2,300	3.01	6.55	4.78
North aspect:				South aspect:			
2,700	3.57	6.14	4.86	2,700	3.41	6.61	5.01
3,800	3.98	6.31	5.14	3,800	2.92	5.66	4.29
5,500	4.64	6.93	5.78	5,500	3.88	6.59	5.24

[1] Priest River Experimental Forest. Length of season: 1935, May 22–Oct. 7; 1936, May 20–Oct. 2.

The 1937–38 precipitation records from the Forest Service gages (table 4) exhibited similar relationships between aspects. Measurements from the previously described sloped-orifice gages exposed in pits (table 4) showed, however, no significant difference between the catch on north and south slopes. Rainfall on south slopes for the two seasons as caught by the pit-exposed gages was 101 percent of the north-slope catch at 5,500 feet, 100 percent at 3,800 feet, and 98 percent at 2,700 feet. These data indicate that there was no significant difference in fall between the north and south sides of this ridge.

TABLE 4.—*Precipitation during summers of 1937 and 1938*[1] *as measured by Forest Service rain gages in elevated exposure at 8 stations and sloped-orifice, pit-exposed gages at 6 stations*

Situation and elevation (feet)	Forest Service gage			Sloped-orifice gage		
	1937	1938	Mean	1937	1938	Mean
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Partly timbered: 2,300	11.64	4.55	8.10			
North aspect:						
2,700	10.82	4.62	7.72	11.19	4.75	7.97
3,800	11.36	4.75	8.06	11.47	4.90	8.18
5,500	12.99	5.61	9.30	13.87	5.71	9.79
Fully exposed: 2,300	10.61	4.54	7.58			
South aspect:						
2,700	10.22	4.51	7.36	10.88	4.69	7.78
3,800	10.21	4.41	7.31	11.50	4.82	8.16
5,500	10.50	5.30	7.90	13.94	5.85	9.90

[1] Priest River Experimental Forest. Length of season: 1937, June 1–Oct. 6; 1938, June 8–Oct. 10.

Both tables 3 and 4 endorse the universally recognized fact that precipitation is greater at high elevations than at low. According to

Henry (*8*), altitudinal differences are less during summer months than in winter, especially when summer months are relatively dry as they are on the study area. Summer storms are predominantly convectional and cross the area at random with equal probability of centering near the high or low end of the forest. Individual storms frequently furnished more rain to the low than to the high stations; but over the course of a season or more, precipitation totaled more at the higher stations.

Fuel Moisture

Since precipitation is of consequence in this study only because it increases fuel moisture and thereby lowers the fire-behavior class, the true measure of its significance at different altitudes and aspects will not be the amount that falls at each station but the period during which fire danger is alleviated by each rain. Table 5 shows the average number of days [11] that ½-inch-wood and duff moisture content failed to drop to or below 10 percent for each day on which 0.01 inch or more rain fell at over one-half of the eight stations. Ten percent is used because it is the upper limit of high inflammability of duff as determined by Gisborne (*5*) for the region in which the study was conducted. Rain of 0.01 inch or more fell at a majority of the eight stations on an average of 26.2 days per season of 4 months, June to September. For each rainy day, ½-inch-wood moisture remained above 10 percent for 0.8 to 1.8 days and duff moisture for 0.7 to 2.3 days at the various stations.

TABLE 5.—*Average number of days per day of rain (0.01 inch or more) that fuel moisture remained above 10 percent at the majority of stations, June to September 1935–38*

Type of fuel and elevation (feet)	1935 (26 days)	1936 (28 days)	1937 (29 days)	1938 (22 days)	Average 1935–38 (26.2 days)
½-inch wood:	*Days*	*Days*	*Days*	*Days*	*Days*
Partly timbered: 2,300	1.5	1.1	2.5	2.0	1.8
North aspect:					
2,700	1.2	1.1	1.8	1.9	1.5
3,800	1.2	1.1	1.3	1.3	1.2
5,500	1.4	1.2	1.4	1.7	1.4
Fully exposed: 2,300	.9	.8	1.0	.7	.8
South aspect:					
2,700	1.0	.8	1.1	1.0	1.0
3,800	1.1	1.1	1.2	1.2	1.2
5,500	1.5	1.2	1.3	1.3	1.3
Duff:					
Partly timbered: 2,300		2.6	1.9	2.2	2.3
North aspect:					
2,700		1.5	2.0	1.9	1.8
3,800		1.8	1.4	1.7	1.6
5,500		1.7	1.2	1.3	1.4
Fully exposed: 2,300		.8	1.0	.7	.9
South aspect:					
2,700		.7	.7	.6	.7
3,800		.9	.9	.8	.8
5,500		1.0	.9	.9	1.0

Table 5 gives no indication that the difference in amount of rain received at the different altitudes from the average storm significantly affects the length of time that high inflammability is prevented. The

[11] The day considered in this compilation is 10 a. m. to 10 p. m. If, at any time between 10 a. m. and 10 p. m., ½-inch wood or duff moisture reached 10 percent or below, the day was not counted.

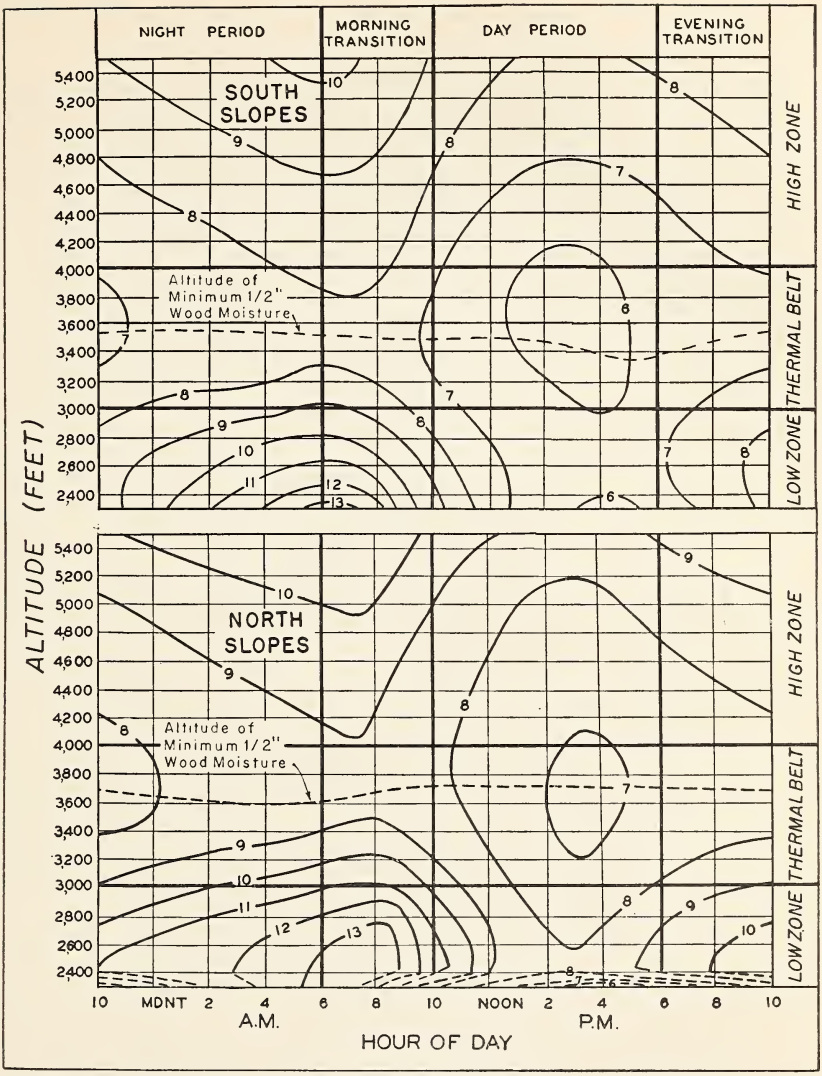

FIGURE 9.—Isograms showing the daily cycle of ½-inch wood-cylinder moisture content for the median day of August 1935–38, at various altitudes on south and north slopes. The broken isograms represent the transition from valley bottom to lowest north-aspect conditions, which is apparently abrupt.

exposure of each station to drying influences after the rain is the stronger determinant of the time fuels remain above the danger point. On south slopes, where insolation is dominant, duff dried more rapidly than ½-inch wood, while on the north slopes ½-inch wood dried the more rapidly. On south slopes both fuels dried earliest at low elevations and progressively slower in the higher zones where fog and clouds persist longer after storms. On north slopes, however, duff dried first in the high zone despite the persistence of fog and cloud at this eleva-

tion, whereas ½-inch wood dried first in the thermal belt. Both types of fuel dried more slowly at the partially timbered valley-bottom station than at any other.

In the absence of rain the daily ebb and flow of ½-inch-wood-moisture is determined mainly by temperature and relative humidity. The thermal belt at midaltitudes, which has been shown to be a zone of sustained high temperature and low humidity, is now evident in figure 9 as a zone of sustained dryness of branch wood. The thermal belt is not only the driest at night, but it is the driest of the altitudinal zones during the day period also for both north and south aspects. Half-inch wood becomes so moist at night in the low zone that the high temperatures and low humidity of the day period do not reduce it to the dryness which occurs in the thermal belt. Fires originating where wood is the major fuel will need more prompt and aggressive suppression action within the thermal belt than either above or below, regardless of aspect or time of day.

On south slopes the low zone was more moist than either the thermal belt or high zone from 8 p. m. until 1 p. m., a period of 17 hours, and intermediate between them for the remaining 7 hours of the most critical burning period of the day. The high zone, most moist for the 7-hour period, was midmoist for the remaining 17.

On north slopes the low zone remained more moist than either the thermal belt or high zone for the entire 24 hours, indicating that low north slopes are the easiest of the nontimbered areas studied on which

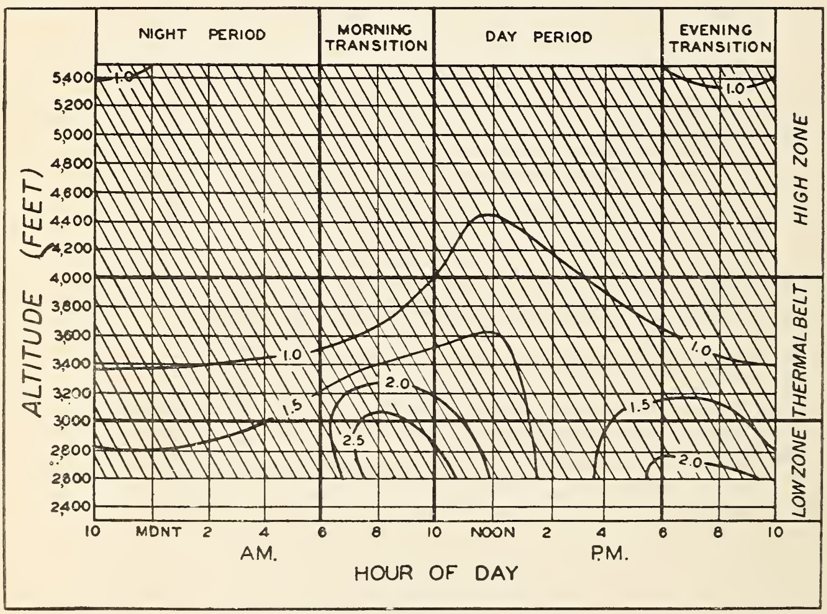

FIGURE 10.—Isograms showing the daily cycle of the difference between north- and south-aspect ½-inch-wood moisture for the median day of August 1935–38, at various altitudes. The isograms are discontinued near the valley-bottom base elevation where north and south aspects cease to exist. On shaded portions (in this case the entire chart) north-aspect values are greater than south.

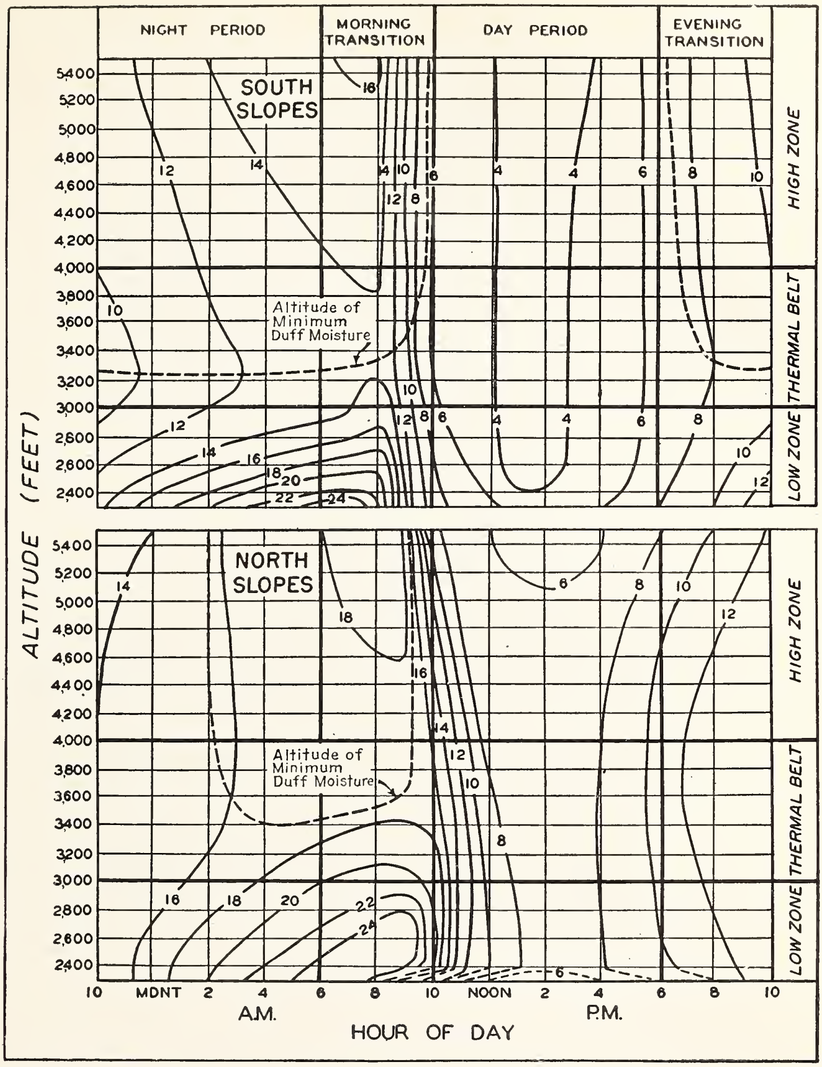

FIGURE 11.—Isograms showing the daily cycle of duff moisture content for the median day of August 1936–38, at various altitudes on south and north slopes. The broken isograms represent the transition from valley bottom to lowest north-aspect conditions, which is apparently abrupt.

to control fire both night and day. The north-aspect high zone was intermediate in wood moisture content between the other two.

According to figure 10, north-aspect wood was more moist than south at all hours and all altitudes. The difference between aspects was greatest at low altitudes and lessened progressively as altitude increased, further substantiating previous indications that the higher the altitude the more north-aspect conditions tend to be like south. Mean daily excess of wood moisture on north slopes was 1.9 percent at

2,700 feet, 1 percent at 3,800 feet, and 0.9 percent at 5,500 feet elevation. The smallest difference occurred during the night period at all altitudes, culminating in the high zone at 6 a. m., and the greatest difference during the morning and evening transition periods in the low zone and during the day period in the higher zones.

Duff is the most extensive fine fuel found in contact with the ground. The daily ebb and flow of duff moisture is determined by air temperature and relative humidity, modified by insolation and soil moisture. In figure 11, showing the daily fluctuations of duff moisture, the thermal belt again proved to be a zone of sustained dryness of fuel.

On south slopes duff moisture followed the typical altitude and fuel-moisture relationship during the evening transition, night, and morning-transition periods. The thermal belt was driest, the low zone most moist, and the high zone midmoist. After the sun became high enough in the sky to start insolational drying, however, a rapid adjustment took place. Duff moisture became approximately the same at all altitudes by 10 a. m. and remained the same throughout the day period. The inflammability of duff was uniform at all altitudes for south exposures during the most critical part of the daily burning period but was greatest in the thermal belt, next in the high zone, and lowest in the low zone for the remainder of the day.

On north slopes the thermal belt was also a zone of sustained duff dryness, but the high zone was even drier for much of the day. The high zone was the driest from about 9 a. m. until 2:30 a. m., a period of 17½ hours, and was midmoist for the remaining early morning hours. The thermal belt was the driest during these few early hours and midmoist during the other 17½ hours. Thus duff was most moist in the low zone for the entire 24 hours of the median August day on north slopes. At the time of minimum daily duff moisture, about 2 p. m., moisture content was practically the same at all altitudes. Approach to the minimum in moisture content was maintained for a much longer period at high altitudes than at low, however, making the average inflammability of duff during the critical burning period greatest at high altitudes and progressively less as altitude decreased. Night or day, duff fires on north slopes will be the easiest to control in the low zone and of greater but approximately equal difficulty in the thermal belt and high zone.

At the time of the daily minima, when insolation is a dominating influence, duff moisture is least on south aspects, 1 to 2 percent more moist at the fully exposed valley-bottom station, 2 to 4 percent more moist on north slopes, and 6 to 8 percent more moist at the partly timbered valley-bottom station. The effect of isolation is evident, in that these moisture values run in inverse ratio to the duff-surface maximum temperature values produced by insolation, as shown in table 2.

Duff was more moist on north slopes than on south at all hours and all elevations, as shown by figure 12. The difference between aspects was greatest in the low zone and became progressively less with increasing altitude as already demonstrated for temperature, relative humidity, and moisture content of branch wood. The daily average duff moisture for north aspects was greater than for south by 4.8 percent at 2,700 feet, 4.5 percent at 3,800 feet, and only 1.8 percent at 5,500 feet. The relatively large difference at 3,800 feet is attributed

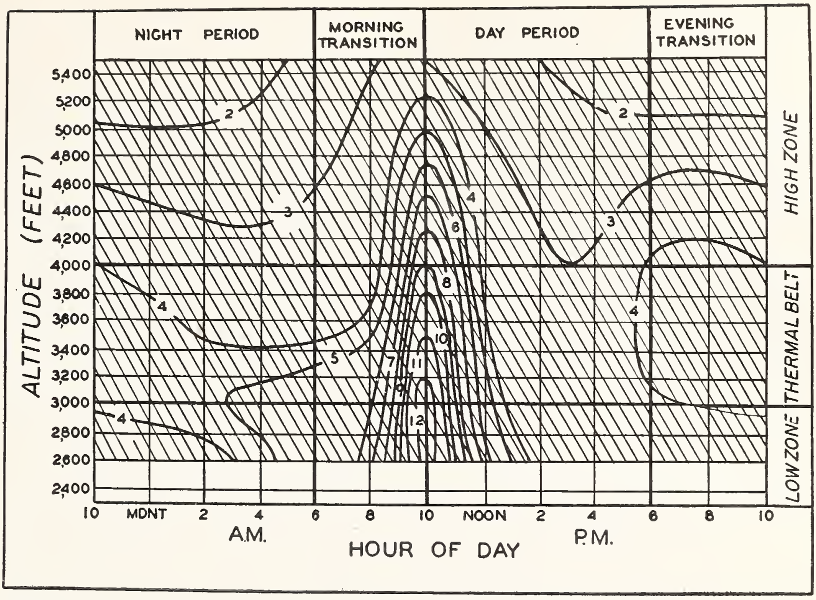

FIGURE 12.—Isograms showing the daily cycle of the difference between north- and south-aspect duff moisture at various altitudes, for the median day of August 1936–38. The isograms are discontinued near the valley bottom where north and south aspects cease to exist. On the shaded portions (in this case the entire chart), north-aspect values exceed south.

to the high timber near the north-side station, which shaded it from the sun's rays during late morning until after insolational drying was well under way on the south side. The least duff moisture difference between aspects occurred between 2 and 4 p. m., whereas the greatest difference occurred between 8 a. m. and noon.

It is evident that in classifying fuel types, rates of spread for similar fuels on north and south slopes should differ much less at high altitudes than at low. This fact has not been recognized by fire-control planners and fuel-type mappers in the past.

The fuel-moisture classes used on the Northern Rocky Mountain fire-danger meter coincide with Gisborne's (*5*) earliest duff inflammability classes with but one additional refinement, the separation of the 7.4 percent or drier group into 7.4 to 5.0 and 4.9 or less. The inflammability classifications assigned in 1928 to the moisture-content groups were:

Moisture group:	*Classification*
18.6 to 25.0	Very low.
13.5 to 18.5	Low.
10.6 to 13.4	Medium.
7.5 to 10.5	High.
7.4 and less	Extreme.

A change of fuel moisture from one group to another changes the class of fire danger produced by the danger meter, sometimes to a degree which is sufficient to require different action on a going fire. This is one of the unavoidable effects of grouping factor measurements, but one which is of small consequence compared to the error of sam-

pling involved when large areas of high and low altitudes, north and south aspect, fully exposed and densely timbered, are rated for fire danger.

According to table 6, the 3,800-foot thermal-belt station was the only one with north aspect at which ½-inch wood dried to extreme inflammability. In the high and low zones on north slopes inflammability varied from high by day to medium at night, while the range in the thermal belt was from extreme to high. On low south slopes and on the fully exposed valley bottom ½-inch wood was extremely inflammable for a third of the 24-hour period, whereas in the thermal belt wood remained in this condition twice as long. During the diurnal cycle on south slopes ½-inch wood varied in inflammability from extreme to low in the low zone; in the thermal belt, from extreme to high; and at highest altitude remained highly inflammable night and day.

Duff, as shown by table 6, covered a wider range than ½-inch wood. It dried to extreme inflammability on the typical August day at all stations except the partly timbered valley bottom and picked up enough moisture at night to be in the low or very low class. On south aspects the greatest average inflammability was at 3,800 feet, but on north aspects at 5,500 feet.

TABLE 6.—*Total hours during which fuels remained in different moisture-content classes at the eight stations, median day of August 1935–38*

Type of fuel, situation, and elevation (feet)	Fuel moisture class (percent)				
	18.6–25.0	13.5–18.5	10.6–13.4	7.5–10.5	0.0–7.4
½-inch wood:	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
Partly timbered: 2,300	0	0	15	9	0
North aspect:					
2,700	0	0	11.5	12.5	0
3,800	0	0	0	16.5	7.5
5,500	0	0	5	19	0
Fully exposed: 2,300	0	1	7	7.5	8.5
South aspect:					
2,700	0	0	2.5	13.5	8
3,800	0	0	0	7	17
5,500	0	0	0	24	0
Duff:					
Partly timbered: 2,300	10	6.5	4	3.5	0
North aspect:					
2,700	7.5	6	4	5	1.5
3,800	0	14	4	3	3
5,500	1.5	8.5	3	4	7
Fully exposed: 2,300	7.5	3.5	2.5	3.5	7
South aspect:					
2,700	0	7.5	4	4	8.5
3,800	0	2	8	4.5	9.5
5,500	0	7.5	4	3.5	9

Table 6 indicates that the average daily rate of spread of fires burning in the mixed fuel common in the northern Rocky Mountain region, with similar winds at all altitudes, would be greater in the thermal belt than in any other zone on south aspects, and that the greatest average rate of spread on north aspects would probably be in the high zone and thermal belt with little difference between them. At the same time, the average rate of spread would be least under the partial timber canopy in the valley and next to lowest on north aspects in the low zone.

These same fuel-moisture classes are also dependable indices of the readiness with which fuel will ignite. Gisborne (*5*) and others have

found that embers with the heat of an ordinary kitchen match are effective firebrands in duff of 10 percent or less moisture content. Similar embers were dangerous duff firebrands on the typical August day for only 3½ hours at the partly timbered station, and on the north slopes for 6½ hours at 2,700 feet, for 6 hours at 3,800 feet, and for 11 hours at 5,500 feet. At the fully exposed valley station similar embers were dangerous for 10½ hours, and at the south aspect stations for 12½ hours at 2,700 feet, 14 hours at 3,800 feet, and 12½ hours at 5,500 feet. The danger of fires starting from small firebrands is present for a shorter period of each day in the valley bottom and low zone than above, and is present for the longest period in the thermal belt on south slopes.

Measurements of fuel-moisture content and of its controlling factors have emphasized the dryness and dangerousness of the thermal belt, and the less dangerous nature of the lower altitudes, especially at night. Before fire behavior can be evaluated by altitude and aspect, however, wind velocity must be considered.

Wind Velocity

Wind, the factor which most frequently whips fires out of control (*6*), passes through a daily cycle in this region as shown (fig. 13) in the daily record of wind velocity on south and north aspects. The trough of the cycle occurs about midnight and the peak between noon and 2 p. m., at the time when all other factors governing fire behavior are most severe.

Unlike fuel-moisture content and its controls, wind is not most dangerous in the thermal belt but is greatest at high elevations and diminishes with decreasing altitude during the evening transition, night, and morning transition periods. During the day period on south slopes however, practically no difference in wind velocity between altitudes is indicated in figure 13, except between the lowest south-aspect station and the valley bottom. Prior to October 1936, when a brush fire swept the slope around the 2,700-foot south-aspect station, less wind was generally recorded there than at either of the stations above. Since the fire, this station has averaged windiest of all during the day period despite efforts to restore the brush field to its previous condition by planting. Resulting 3-year median wind velocities are, therefore, probably higher at the south-aspect 2,700-foot station than they would have been had the fire not disturbed former conditions.

On north slopes (fig. 13) the wind velocity-altitude relationship was the same as for south aspects, except that a slight wind gradient probably existed during the day period also. The true relationships on north slopes were obscured by the presence of the high timber near the 3,800-foot station but with a maximum daily velocity between 3 and 4 miles per hour at 2,700 feet and over 5 miles per hour at 5,500 feet, a velocity-altitude gradient was probably present.

As with other factors of fire behavior, the greatest difference in wind velocity between aspects was in the low zone, the difference becoming progressively less with increasing altitude, as shown by figure 14. At 3,800 feet in elevation the timber near the north-side station obscured the trend by causing a larger difference between aspects than would otherwise be present. The data averages show that south-side winds

were stronger than north-side by 1.5 m. p. h. at 2,700 feet, 1.6 m. p. h. at 3,800 feet, and 1.1 m. p. h. at 5,500 feet in elevation. The least wind-velocity difference between aspects occurred early in the night period; the greatest differences were about 6 a. m., at 5,500 feet; noon, at 3,800 feet; and 2 p. m., at 2,700 feet in elevation.

Therefore, the effect of wind velocity on fire behavior, in common with the effect of fuel-moisture content and its controls, was greater on south aspects than on north and greater during the day than at night. Unlike other factors, however, its effect during the evening

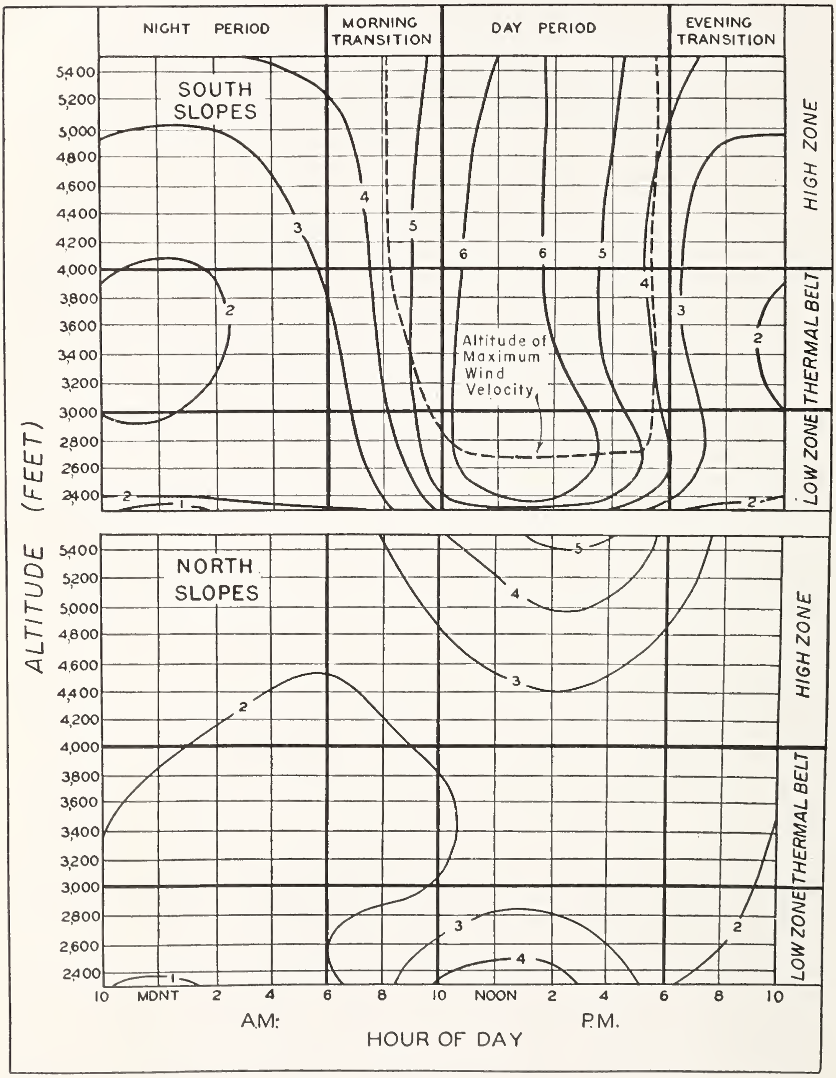

FIGURE 13.—Isograms showing the daily cycle of wind velocity 7½ feet above ground at various altitudes on south and north slopes, for the median day of August 1936–38.

transition, night, and morning transition periods was greatest in the high zone, not the thermal belt, and during the day period its effect was about equal in all zones.

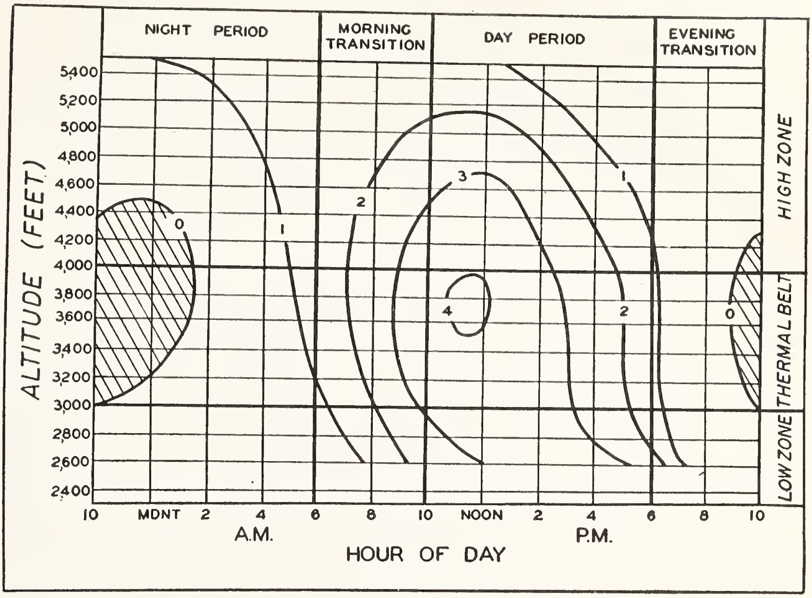

FIGURE 14.—Isograms showing the daily cycle of differences in wind velocity at various altitudes between north and south aspects for the median day of August 1936–38. The isograms are discontinued near the valley-bottom base elevation where north and south aspects cease to exist. On shaded parts of the chart north winds exceed south; on unshaded parts south winds exceed north.

FIRE BEHAVIOR

To obtain fire-behavior ratings, fuel-moisture content and wind velocity were integrated by means of the Model 5 Northern Rocky Mountain fire-danger meter which rates fire behavior on a numerical scale from class 1 to 7. These seven classes embrace the entire range of fire behavior from no spread, under class 1, to explosive conditions with fire spreading at rates up to 1,500 or 2,000 acres per hour even on densely timbered north slopes when class 7 combinations exist.

In figure 15, presenting for August the typical daily cycle of fire behavior on south slopes, the ratings ranged from class 2.4 at the fully exposed valley-bottom station at 6 a. m. to 5.0 in and near the thermal belt during the peak of the fire day. This is a total daily fluctuation of more than one-third the entire recognized range of fire behavior. A similar record made by Hayes,[12] based on the median day of August 1936, the most severe fire month experienced during any of the four seasons of this study, showed that fire behavior ranged through 4, or more than half, of the possible 7 classes during the daily cycle. This emphasizes the great difference in diurnal fire

[12] HAYES, G. L. VARIATIONS OF SOME FIRE DANGER FACTORS WITH ALTITUDE, ASPECT, AND TIME OF DAY. North. Rocky Mountain Forest and Range Expt. Sta., Appl. Forestry Note 80, 6 pp., illus. 1937. [Mimeographed.]

behavior which must be known by the fire dispatcher if fires are to be controlled both at least possible cost and at smallest acreage burned.

It has been shown that when a nocturnal temperature inversion occurs branch wood and duff are most moist on the valley bottom, register a rapid decrease to a minimum moisture content within the thermal belt, and gain moisture slowly above that zone. Figure 15 shows the pronounced effect of this fuel-moisture variable, with fire behavior rating low on the valley bottom, increasing rapidly to a maximum in the thermal belt, and decreasing slowly above. Temperature inversion therefore acts to produce an inversion of fire behavior, with highest rating in the thermal belt, intermediate in the high zone, and lowest in the low zone.

In addition to becoming the most dangerous level on the south aspect at night when the inversion was present, the thermal belt held the maximum fire-behavior rating throughout the greater part of the remaining hours. The high temperature and low humidity in the low zone during the day period tended to lower the level of most dangerous fire behavior, but only for 2 hours was it depressed below 3,000 feet. Even during these 2 hours burning conditions were, for all practical purposes, just as dangerous in the thermal belt as in the higher levels of the low zone. The 3,800-foot station, owing to its persistently high fire-behavior rating, had a daily mean rating of 4.0, while the other south-aspect stations rated 3.8 at 5,500 feet, 3.8 at 2,700 feet, and 3.4 at 2,300-foot, fully exposed station. The difference in fire behavior ratings between the high zone and thermal belt is the same for both the night and day periods. The difference between the low zone and thermal belt is twice as great, however, during the night as during the day period.

The effect of the temperature inversion, acting through fuel moisture on fire behavior, was found to be much less on north slopes than on south. A fire-behavior inversion was evident on north slopes (fig. 15) for only a short time, from midnight to 6:30 a. m. Even then the difference in ratings between the thermal belt and high zone was so small as to be negligible. The considerably lower ½-inch wood moisture in the thermal belt during the night period is largely offset by higher wind velocity in the high zone.

Burning conditions on north slopes become practically the same at all elevations between 2 and 3 p. m. Near-maximum fire-behavior ratings were recorded for a much longer period, however, at high elevations than at low. A rating of 4.0 or more was found for 6 hours at 5,500 feet, for 3 hours at 3,800 feet, and for only slightly more than 1 hour at 2,700 feet. Because of the longer persistence of more dangerous conditions in the high zone, the 5,500-foot station had a daily mean rating of 3.5, while the other north-slope stations rated 3.3 at 3,800 feet, and 3.1 at 2,700 feet. During the day period alone, when burning conditions were most critical, the high zone was most dangerous also, with an average rating of 4.1 at 5,500 feet, while the 3,800-foot level averaged 3.8, and the 2,700-foot level but 3.6. During the night period the inversion influence was strong enough so that the 3,800-foot station rated 3.1, which was 0.1 class higher than at 5,500 feet, and 0.3 class higher than at 2,700 feet.

The tendency on north slopes for the high zone to rate more dangerous than the thermal belt, despite a well-developed temperature

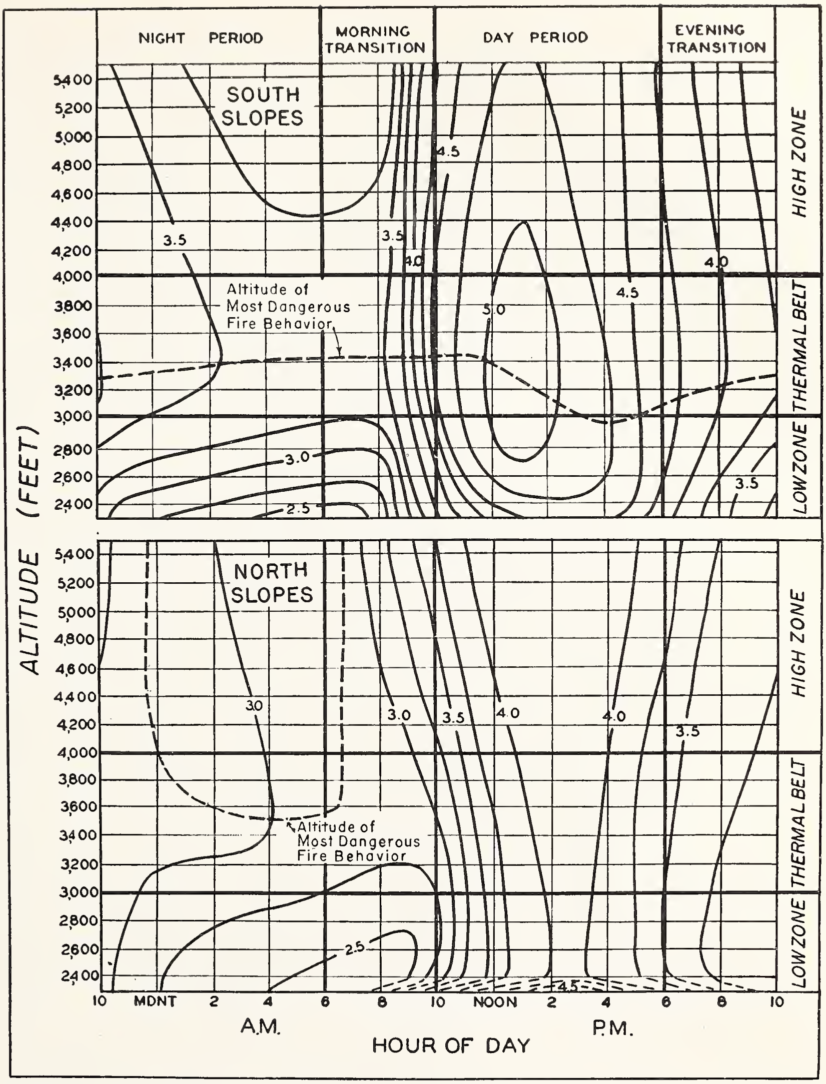

FIGURE 15.—The daily cycle of forest-fire behavior at various altitudes on south and north slopes, for the median day of August 1935–38. The broken isograms represent the transition from valley bottom to lowest north-aspect conditions, which is apparently abrupt.

inversion at night (fig. 5), is attributed in part to the high timber near the 3,800-foot station. This station is shaded from the sun ½ to 2¼ hours later than other north-aspect stations in the morning and from 1¼ to 2 hours earlier in the evening (observations made on August 21). Evidence of the effect of this shading appears in the definitely increasing fire-behavior rating by 8:30 a. m. at 5,500 feet, and not until 9:30 a. m. at 3,800 and 2,700 feet, despite an earlier actual sunrise at 3,800 than at 2,700 feet. If the marked reduction in wind velocity (fig. 13)

undoubtedly resulting from the sheltering timber were removed, the north-aspect thermal-belt station would have the most dangerous daily average rating of all north exposures, just as the south-aspect thermal-belt station has the most dangerous daily average rating of all south exposures.

The table by Hayes for August 1936 alone, already mentioned, gave the 5,500-foot stations a slightly higher rating than those at 3,800 feet on both north and south slopes. There are three possible reasons for these results, in partial contradiction of those shown in figure 15. First, day-period winds of August 1936 were stronger at 5,500 feet than at 3,800 on the south aspect, whereas the average day-period winds of the four Augusts were the same at both altitudes on the south aspect. Second, the 1936 ratings were rounded off to whole behavior classes, whereas those in figure 15 were computed to tenths of classes and closely interpolated. Third, temperature at night decreased less with increasing elevation above the inversion in August 1936 than in the other three Augusts.

The previously noted tendency for north-aspect values of temperature, relative humidity, wind, and fuel moisture to become more like south with increasing altitude is shown by figure 16 to be true of fire-behavior differences between aspects also, especially during the day period. The greatest difference occurred at the beginning of the day period and the smallest differences, in general, during the night period. The fire-behavior rating on the south side exceeded that on the north at all times except on the mountain top from 7 to 9 a. m., when the

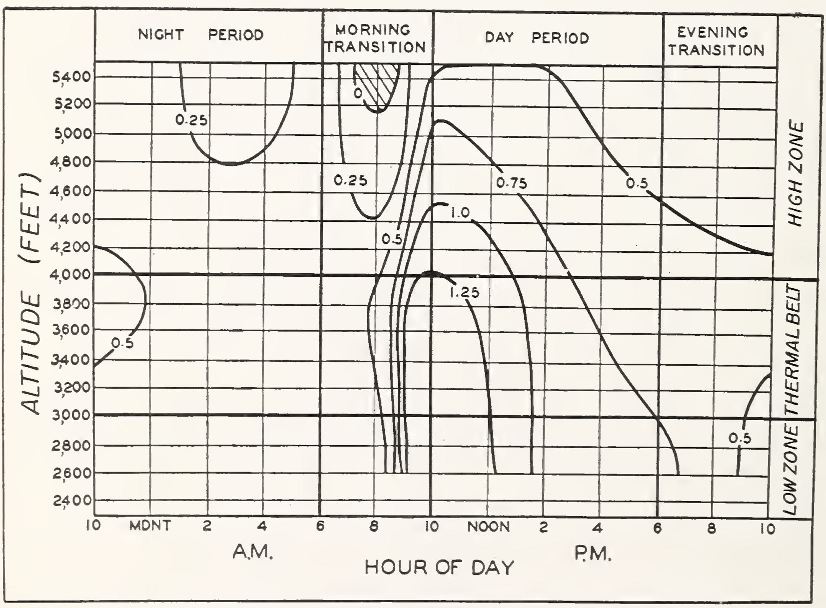

FIGURE 16.—Isograms showing the daily cycle of the differences in fire behavior between north and south slopes, for the median day of August 1935–38. The isograms are discontinued as they approach the valley bottom where north and south aspects do not exist. On the small, shaded portion of the chart north-aspect values are greater; elsewhere, south-aspect values.

north-side rating exceeded the south by only 0.1 class. The south-aspect mean daily fire-behavior rating exceeded that for the north aspect by 0.7 class at 2,700 feet, 0.7 class at 3,800 feet, and 0.3 class at 5,500 feet. The relatively large difference at 3,800 feet is again attributed to the timber near the north-side station.

The influence of a partial timber canopy on fire behavior is well illustrated by the data for the 2,300-foot stations. There the partly timbered station registered a daily mean of only 2.8, which is 0.06 lower than that at the fully exposed station. Of greater significance, however, is the rating of 1.2 lower for the partially timbered station than in the open during the day period when burning conditions are most critical.

If every fire that starts on a forest district is to be controlled with greatest efficiency, the prevailing fire-behavior class must be known with reasonable accuracy at every spot on the district where a fire might occur and at every hour of the day. It has been shown that over one-third the total recognized range of fire behavior is represented between the highest and lowest ratings obtained on the typical August day. At the fully exposed valley-bottom station alone, the fire-behavior rating varied as much as 2.3 from its minimum at 6 a. m. to its maximum at 2 p. m., and at any hour of the day considerable differences were found between stations. At 4 a. m., when all stations rated most similar, a range of 0.8 was present, while at 10 a. m., when they rated most diverse, the range was 1.9. In view of these considerable differences, how is a fire dispatcher to determine how many men to send to insure safe control of a new fire? He must send to every fire that starts, regardless of location or time of day, adequate men to insure control within allotted time limits and yet, for efficiency and economy, the job must be done with as few men as possible.

Before determining how many men to send, several factors must be considered. Outstanding among these is the rate at which the fire will spread and the resistance it will offer to control. Resistance to control can be approximated from the forest-fuel-type map, and rate of spread can be determined with reasonable accuracy from information obtained from the fuel-type map and a rate-of-spread meter, provided the fire-behavior rating is known at the spot where the fire is located. However, the nearest inflammability station at which measurements are made but once a day at 4:30 p. m. may be located several miles away, either at a valley-bottom ranger station or a mountaintop lookout station. This obstacle may be partly overcome by using such information as is given for a typical August day in figure 15. After studying these charts, a more reliable estimate of the fire-behavior class prevailing at any spot at any time of day should be possible.

SUMMARY OF RESULTS

This research was conducted to determine how forest-fire behavior and its controlling variables differ between altitudes throughout the day on north and south slopes.

Observations were made at eight stations, six of them paired on north and south aspects at 5,500-, 3,800-, and 2,700-foot elevations, and within 50-foot elevation of the top of a ridge rising from west to east on the Priest River Experimental Forest. The other two were valley-bottom

stations, one fully exposed to sun and wind and the other with a partial timber canopy.

The variables observed were wind velocity and fuel-moisture content as affecting fire behavior, and air temperature, relative humidity, insolation, soil moisture, and precipitation as largely controlling fuel-moisture content.

Three altitudinal zones and four time periods having different characteristics on the median August day are recognized. The zones are the high zone, lying above 4,000 feet, the thermal belt from 4,000 to 3,000 feet, and the low zone below 3,000 feet elevation. The periods are the night period from 10 p. m. to 6 a. m., the morning-transition period from 6 to 10 a. m., the day period from 10 a. m. to 6 p. m., and the evening-transition period from 6 to 10 p. m.

During the night period the vertical gradients of most of the factors studied have an inversion centering in the thermal belt. Inversions of relative humidity and fuel-moisture content are brought about by the recurring nocturnal temperature inversions. As a consequence, and despite night-period wind velocities which increase directly with altitude, an inversion of fire behavior is formed with most dangerous burning conditions in the thermal belt, middangerous in the high zone, and least dangerous in the low zone.

During the day period the various factors affect the altitude and fire-behavior relationship differently. Temperature and relative humidity tend to effect most dangerous conditions in the low zone, while ½-inch wood remains most inflammable in the thermal belt. Duff on north slopes becomes driest in the high zone, but on south slopes is quite equally dry at all elevations. Likewise, wind on north slopes is strongest in the high zone but on south slopes is nearly equal at all elevations. Resulting fire behaviors on south slopes are slightly more dangerous in the thermal belt than above or below, while on north slopes the greater danger is in the high zone.

The morning- and evening-transition periods are, as their names imply, times of changes from night to day relationships and vice versa.

Fire behavior was found, as expected, to be more dangerous during the day than at night and more dangerous on south slopes than on north. Less difference in fire-behavior rating between day and night conditions and between aspects was found at high elevations than at low, however, indicating that the higher the elevation, the more burning conditions at night tend to be like day conditions, and the more north-aspect conditions tend to be like south-aspect.

Of the minor factors affecting fire behavior, insolation was found to be the dominant control of duff moisture content during midday on south aspects, a major but less dominant control on the fully exposed valley bottom, and of less importance as a control of duff moisture on north aspects and under a partial timber canopy.

Soil moisture was found to be affecting duff moisture at all locations at night, but only on north aspects and under a partial timber canopy during the hot part of the day. The difference in amount of rain received at the different stations from the average summer rain did not significantly affect the time during which inflammability was reduced. The exposure of each station to drying influences was the stronger determinant.

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